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13. ABSTRACT (Maximum 200 words)

The program has (1) developed prototype microwave soliton delay line devices; (2) developed new device concepts based on the phase and velocity characteristics of solitons; and (3) applied Brillouin light scattering techniques to soliton characterization. New types of solitons, in the form of "dark" surface wave solitons and backward volume wave solitons for in-plane magnetized yttrium iron garnet (YIG) films, were generated, detected, and modeled. Soliton formation, propagation, decay, reflection and collision properties were measured and modeled on the basis of the one dimensional nonlinear Schrödinger equation. Parametric pumping and feedback techniques were developed to amplify solitons and self generate eigenmode soliton signals. Brillouin light scattering (BLS) experiments were able to sample directly the wave vector make-up of the soliton signals. Soliton pumped spin waves were also observed and analyzed by the BLS technique. In addition, (1) time and space resolved capability has been added to the BLS system; (2) a new space and time resolved inductive magnetodynamic probe (IMP) technique has been developed and applied to the characterization of soliton delay line devices; (3) a new frequency filtering technique has been used to self generate trains of both bright and dark solitons and produce a phase locked frequency comb. (200 words)

14. SUBJECT TERMS
Microwave magnetic solitons, ferrite films, microwave devices, soliton feedback, Brillouin light scattering, time and space resolved microwave probes, soliton trains, dark solitons, nonlinear microwave delay lines, nonlinear microwave processes in ferrite films, soliton numbers, soliton threshold powers, inductive magnetodynamic probe

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to the
UNITED STATES ARMY RESEARCH OFFICE

Microwave Magnetic Solitons in Ferrite Films - Physics and Devices for Radar, Electronic Countermeasures, and Surveillance

Contract DAAG55-98-1-0430
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July 1, 1998 - September 30, 2001

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STATEMENT OF PROBLEM STUDIED

ARO Grant DAAG55-98-1-0430 has supported a research program to (1) develop prototype soliton switching, parametric amplification, and decay free delay line devices; (2) develop new device concepts based on the phase and velocity characteristics of solitons; (3) apply Brillouin light scattering techniques to beam soliton characterization and to time resolved soliton formation processes. Significant progress has been made in these areas of microwave magnetic envelope (MME) soliton research. New types of solitons, in the form of "dark" surface wave solitons and backward volume wave solitons for in-plane magnetized yttrium iron garnet (YIG) films, were generated, detected, and modeled. Soliton formation, propagation, decay, reflection and collision properties were measured and modeled on the basis of the one dimensional nonlinear Schrödinger equation. Parametric pumping and feedback techniques were developed to amplify solitons and self generate eigenmode soliton signals. Brillouin light scattering (BLS) experiments on propagating soliton pulses were successfully carried out for the first time. These BLS measurements sampled directly the wave vector make-up of the soliton signals. Soliton pumped spin waves were also observed and analyzed by the BLS technique. There have been three very recent developments: (1) time and space resolved capability has been added to the BLS system; (2) a new space and time resolved inductive magnetodynamic probe (IMP) technique has been developed and applied to the characterization of soliton delay line devices; (3) a new frequency filtering technique has been used to self generate trains of both bright and dark solitons and produce a phase locked frequency comb. This work has been featured in several recent Physical Review Letters and Applied Physics Letters, conference symposia, and invited talks.

SUMMARY OF THE MOST IMPORTANT RESULTS

a. Overview

The microwave magnetic envelope (MME) soliton program has had, as stated in the original proposal abstract, three thrusts: (1) prototype soliton switching, parametric amplification, and decay free delay line devices; (2) development of new device concepts based on the phase and velocity characteristics of solitons; (3) application of Brillouin light scattering to beam soliton characterization and to time resolved soliton formation processes.

This section provides a summary of the work accomplished during the grant. Most of the results relate to long and narrow yttrium iron garnet (YIG) thin films excited by a microwave pulses applied to a microstrip antenna across the strip. The pulses are detected by a second antenna at a different position along the strip. The primary excitations here are dipolar magnetostatic wave (MSW) pulses. At high input power levels, these MSW pulses can form solitons.

For continuity and clarity, some of the accomplishments summarized below include, in addition to work under the current grant, DAAG55-98-1-0430, work from the previous funding period under DAAH-95-1-0395. The sections below track the three thrust areas in the original proposal. In order to keep the overview compact and direct, citations to published papers are omitted here. Archival papers and presentations are listed in a separate section.

1. MME solitons and devices for switching, amplification, and signal processing

The previous and just ended grant resulted in the first experimental work in the USA on high frequency envelope solitons in magnetic thin films. Microwave magnetic envelope (MME) solitons, in the form of "dark" magnetostatic surface wave (MSSW) solitons and backward volume wave (MSBVW) solitons for in-plane magnetized films have been generated, detected, and modeled theoretically. Soliton formation, propagation, decay, reflection, and collision properties were measured. The one dimensional nonlinear Schrödinger equation was used to model these signals.

Techniques to switch soliton signals on and off by the application of cw signals were developed. Some work carried over from the previous to the current grant period was directed at the controlled switching of soliton output signals between different ports of a multi-port transducer structure. It was found that cross talk limited the usefulness of such a switch.

Work started in the previous grant period on soliton trains in resonant ring structures was extended to produce decay free soliton pulse sequences under various conditions. (1) Trains of solitons could be produced through self generation, with no input pulse whatsoever. (2) Both bright and dark soliton trains in one and the same ring. (3) Antenna structures with specially designed frequency filtering characteristics, in combination with feedback, were used to produce trains of both fundamental dark solitons and bright solitons. All of these configurations yield frequency power spectra which corresponds to a phase locked comb of frequencies.

2. Soliton and narrow pulse device concepts

Several new nonlinear effects were discovered near the beginning of the current grant period. As a result, the singular focus on soliton devices was expanded to include new device concepts based on these effects. These effects, which include bistability and foldover in nonlinear ferromagnetic and magnetostatic mode resonance and the generation of parametric spin waves through three magnon splitting, have led to a rich variety of new and useful signal processing device concepts.

Especially noteworthy accomplishments from this work concern the production of ultra short 1-2 ns wide microwave pulses from pulses with widths up to 100 - 1000 ns. It is to be emphasized that this short pulse generation does not involve solitons, but the generation of half frequency spin waves. The various frequency and input power conditions needed to produce the ultra short pulses were examined in detail. Standard as well as space and time resolved Brillouin light scattering techniques were used to verify the role of the three magnon splitting process in the observed response. Extensive work was also done on bistable nonlinear magnetostatic wave and magnetostatic mode

interactions, with direct applications to microwave switching and limiter devices.

3. Time and space resolved Brillouin light scattering and inductive probe techniques

Over the years, the Colorado State University (CSU) group has been a key contributor to the development of Brillouin light scattering (BLS) as a versatile probe of magnetic excitations in metallic thin films, bulk ferrite, and ferrite films. The group pioneered the frequency and wave vector selective BLS technique to probe parametric spin waves as well as the usual linear normal mode magnetic excitations in a variety of materials. Much of this work was supported by the ARO. A previous Air Force grant in the middle 1980's was used to develop the BLS technique as a diagnostic tool for magnetostatic wave devices. The National Science Foundation (NSF) has also provided support for the fundamental aspects of the BLS research.

In the course of the just ended grant, the BLS technique has been established as modern probe of MME soliton properties. After the discovery of the ultra short pulse effect discussed above, the technique was also used to map the three magnon splitting processes which drive the effect. Through frequency and wave vector selective BLS measurements, it was possible to observe directly the half frequency spin waves generated in the splitting process and verify that the excited modes were in the expected range of wave vectors. Very recent (and ongoing) work with the new time and space resolved BLS system reveals the dynamics of the short pulse formation and the associated magnon generation.

The soliton work to date shows that a critical aspect in the nonlinear dynamics is the phase profile of the signal. While BLS is a unique probe of fundamental magnetic excitations, the technique cannot access phase. The BLS measurement is also rather exacting. It requires a careful and delicate optical alignment and high signal to noise photon counting. For these reasons, a companion inductive magnetodynamic probe (IMP) technique has been implemented. Here, one uses a small 100 μm scale inductive loop to detect the surface fields associated with the propagating magnetodynamic waves. One detects the time varying microwave fields and obtains, thereby, both amplitude and phase information. The CSU system has both space and time resolved capability. The BLS and inductive probe techniques compliment each other. The BLS probe can yield wave vector information, while the inductive probe can yield phase information. The IMP technique can also be converted to electrodynamic detection by replacing the loop with an open ended coaxial line with an extended center conductor of small dimension.

b. Education and Human Resources

Personnel supported and degrees granted during the current grant period are indicated below. A listing of specific personnel is given in the last section of this report.

High school summer apprenticeships:	5
Undergraduate work study students:	5
Undergraduate degrees:	3
Apprentice students (Germany)	2
Graduate students:	5
Master of Science degrees:	5
Ph.D. degrees granted:	0
Postdoctoral fellows:	8
Visiting scientists:	7

c. Publications and Presentation Statistics

Publications and presentations produced under the just ended grant are listed in the next section. Statistics for the program are indicated below.

Archival journal publications (including accepted, in press publications but not conference proceedings):	19
Conference proceedings articles (in press)	2
Journal articles submitted:	2
Journal articles in preparation:	3
Presentations:	23

The above publications include:

Physical Review Letters:	5
Applied Physics Letters	1
Physical Review B:	2
Journal of Applied Physics:	3

d. Collaborations and connections

The CSU group has an ongoing interaction with the group of Professor Mark Ablowitz in the Department of Applied Mathematics at the University of Colorado at

Boulder. Professor Ablowitz' group is interested in, among other things, the electromagnetic basis of the NLS equation in magnetics, two dimensional soliton processes in nonlinear optics, and the slow approach collision problem. Other theoretical collaborations include Professor Andrei Slavin at Oakland University, Rochester Michigan and Professor Craig Zaspel, Montana State University, Bozeman.

There have also been extensive international collaborations. We maintain an intensive cooperation with the group of Professor Boris Kalinikos at the St. Petersburg Electrotechnical University, St. Petersburg, Russia and Professor Yuri Fetisov at the Moscow Institute of Radioelectronics and Automation. We will also continue a strong collaboration with the group of Professor Burkard Hillebrands, University of Kaiserslautern, Germany.

Industrial collaborations include Dr. J. Douglas Adam at Northrop Grumman Corporation, Baltimore, Maryland, Mr. Elwood Hoakenson at TransTech, Adamstown, Maryland, Drs. Somnath and Louise Sengupta, Paratek Corporation, Columbia, Maryland, and Dr. William Capogeannis, President, OmniYIG, Inc., Santa Clara, California. It is anticipated that during the course of the renewal program, it will be possible to establish significant collaborations with OmniYIG, Inc., for the production of prototype YIG film soliton devices and ferromagnetic metallic film filter devices.

PUBLICATIONS AND PRESENTATIONS

a. Publications:

1. "Observation of self-generation of dark envelope solitons for spin waves in ferromagnetic films," B. A. Kalinikos, N. G. Kovshikov, and C. E. Patton, Pis'ma Zh. Eksp. Teor. Fiz. 68, 229-233 (1998) [JETP Lett. **68**, 243-247 (1998)].
2. "Active magnetostatic wave delay line," Y. K. Fetisov, P. Kabos, and C. E. Patton, IEEE Trans. Magnetics **34**, 259-270 (1998).
3. "Brillouin light scattering and magnon wave vector distributions for microwave magnetic envelope solitons in yttrium iron garnet thin films," H. Xia, P. Kabos, H. Y. Zhang, P. Kolodin, and C. E. Patton, Phys. Rev. Lett. **81**, 449-452 (1998).
4. "Amplification of microwave magnetic envelope solitons in thin yttrium iron garnet films by parallel pumping," P. A. Kolodin, P. Kabos, C. E. Patton, B. A. Kalinikos, N. G. Kovshikov, and M. P. Kostylev, Phys. Rev. Lett. **80**, 1976-1979 (1998).
5. "Calculation of the formation time for microwave magnetic envelope solitons," R. A. Staudinger, P. Kabos, H. Xia, B. T. Faber, and C. E. Patton, IEEE Trans. Magnetics **34**, 2334-2338 (1998).
6. "Phase profiles of microwave magnetic envelope solitons," J. M. Nash, P. Kabos, R. Staudinger, and C. E. Patton, J. Appl. Phys. **83**, 2689-2699 (1998).
7. "On the velocity characteristics of microwave magnetic envelope solitons," H. Xia, P. Kabos, R. A. Staudinger, and C. E. Patton, Phys. Rev. **B58**, 2708-2715 (1998).
8. "Modeling of microwave magnetic envelope solitons in thin ferrite films through the nonlinear Schrödinger equation," H. Y. Zhang, P. Kabos, H. Xia, R. A. Staudinger, P. A. Kolodin, and C. E. Patton, J. Appl. Phys. **84**, 3776-3785 (1998).
9. "Self-generation of microwave magnetic envelope soliton trains in yttrium iron garnet thin films," B. A. Kalinikos, N. G. Kovshikov, and C. E. Patton, Phys. Rev. Lett. **80**, 4301-4304 (1998).
10. "Excitation of bright and dark microwave magnetic envelope solitons in a resonant ring," B. A. Kalinikos, N. G. Kovshikov, and C. E. Patton, Appl. Phys. Lett. **75**, 265-267 (1999).
11. "Microwave magnetic envelope solitons in thin ferrite films," C. E. Patton, P. Kabos, H. Xia, P. A. Kolodin, H. Y. Zhang, R. Staudinger, B. A. Kalinikos, and N. G. Kovshikov, J. Mag. Soc. Japan **23**, 605-610 (1999).
12. "Microwave bistability in a magnetostatic wave interferometer with external feedback," Y. K. Fetisov and C. E. Patton, IEEE Trans. Magnetics **35**, 1024-1036 (1999).
13. "Nonlinear ferromagnetic resonance and foldover in yttrium iron garnet thin films - Inadequacy of the classical model," Y. K. Fetisov, C. E. Patton, and V. T. Synogach, IEEE Trans. Magnetics **35**, 4511-4521 (1999).
14. "Modeling of the power dependent velocity of microwave magnetic envelope solitons in thin films," C. E. Zaspel, P. Kabos, H. Xia, H. Y. Zhang, and C. E. Patton, J. Appl. Phys. **85**, 8307-8311 (1999).
15. "Brillouin light scattering observation of the nonlinear spin wave decay in yttrium iron garnet thin films," H. Y. Zhang, P. Kabos, H. Xia, P. A. Kolodin, and C. E. Patton, Phys. Rev. **B61**, 522-528 (2000).

16. "Ultra short microwave pulse generated due to three magnon interactions," V. T. Synogach, Y. K. Fetisov, C. Mathieu, and C. E. Patton, Phys. Rev. Lett. **85**, 2184-2187 (2000).
17. "Suppression of microwave magnetic envelope solitons by cw magnetostatic wave signals," M. M. Scott, Y. K. Fetisov, V. T. Synogach, and C. E. Patton, J. Appl. Phys. **88**, 4232 (2000).
18. "The self generation of fundamental dark solitons in magnetic films," B. A. Kalinikos, M. M. Scott, and C. E. Patton, Phys. Rev. Lett. **84**, 4697-4700 (2000).
19. "Spin wave instability in single crystal Zn-Y hexagonal ferrite at 8.93 GHz," R. G. Cox, C. E. Patton, M. A. Wittenauer, P. Kabos, and L. Chen, J. Appl. Phys. 89, 4454-4469 (2001).
20. "Microwave bistability in nonlinear thin film ferromagnetic resonator," Y. K. Fetisov and C. E. Patton, J. Elec. Comm. Tech., in press (2001). In Russian
21. "Time domain MOKE detection of spin wave modes and precession control for magnetization switching in ferrite films," M. Bauer, R. Lopusnik, H. Dötsch, B. A. Kalinikos, C. E. Patton, J. Fassbender, and B. Hillebrands, J. Magn. Magn. Mat., in press (2001).
22. "Brillouin light scattering analysis of ultra short microwave pulse formation processes in yttrium iron garnet films," C. Mathieu, V. T. Synogach, and C. E. Patton, J. Mag. Soc. Japan, in press (2001).
23. "General spin wave instability theory," A. V. Nazarov, R. G. Cox, and C. E. Patton, IEEE Trans. Magnetics, submitted (2000).
24. "Self-generation of bright microwave magnetic envelope soliton trains in ferrite films through frequency filtering," M. M. Scott, B. A. Kalinikos, and C. E. Patton, Appl. Phys. Lett. **78**, 970-972 (2001).

b. Presentations

1. "Microwave magnetic envelope solitons in thin films," IBM Watson Research Center, Yorktown Heights, New York, July 16, 1998.
2. "Magnetics research at Colorado State University," Materials Research Laboratory, Pennsylvania State University, July 20, 1998.
3. "Microwave magnetic envelope solitons in thin ferrite films," International Symposium on Physics of Magnetic Materials, Sendai, Japan, August 25, 1998.
4. "Microwave soliton devices," Northrop Grumman Research and Development Center, Pittsburgh, Pennsylvania, September 11, 1998.
5. "Microwave magnetic solitons in thin films," XIVth International Conference on Microwave Ferrites, Gyromagnetic Electronics, and Electrodynamics, Eger, Hungary, October 12, 1998.
6. "Microwave envelope soliton devices," XIVth International Conference on Microwave Ferrites, Gyromagnetic Electronics, and Electrodynamics, Eger, Hungary, October 12, 1998.
7. "Precessing magnets and the Landau Lifshitz equation," Joint Seminar sponsored by the Colorado Center for Information Storage and IEEE Magnetics Society, University of Colorado at Boulder, October 22, 1998.
8. "Bistability in a nonlinear ferromagnetic resonance resonator," 43rd Annual Conference on Magnetism and Magnetic Materials, Miami, Florida, November 10, 1998.
9. "The physics of envelope solitons," Seminar, Department of Physics, University of Maryland, College Park, Maryland, November 20, 1998.
10. "Generation, propagation, and amplification of microwave magnetic envelope solitons in ferrite films," Centennial Meeting of the American Physical Society, Atlanta, Georgia, March 23, 1999.
11. "Microwave magnetic envelope solitons in ferrite films," Seminar, Department of Physics, Texas A&M University, College Station, Texas, May 21, 1999.
12. "Microwave magnetic envelope solitons in ferrite films - a tutorial on envelope solitons," Advanced Materials Research Institute, University of New Orleans, New Orleans, Louisiana, May 24, 1999.
13. "Ferrite materials for microwave and millimeter wave applications," Office of Naval Research Workshop on Ultra Wideband, High Power Circulators and Isolators for Advanced Multifunction RF System (AMRFS), June 25, 1999.
14. "Magnetic oxides," Lecture, AG Hillebrands, Fachbereich Physik, Universität Kaiserslautern, Germany, October 25, 1999.
15. "Microwave magnetic envelope solitons in thin films," Lecture: Department of Physics, Universität Regensburg, Regensburg, Germany, November 3, 1999; Institut für Experimentalphysik, Freie Universität Berlin, Germany, February 21, 2000; Max Planck Institut für Mikrostrukturphysik, Halle, Germany, February 22, 2000; Department of Applied Physics, Kiev Taras Schvchenko University, Kiev, Ukraine, March 16, 2000; Van der Waals Zeeman Institute, University of Amsterdam, The Netherlands, March 21, 2000; Technische Universität Carolo-Wilhelmina, Braunschweig, Germany, May 4, 2000.
16. "Nonlinear magnetic excitations," Lecture, AG

Hillebrands, Fachbereich Physik, Universität Kaiserslautern, Germany, November 15, 1999.

17. "A romp through microwave damping and relaxation - Part I," Lecture: AG Hillebrands, Fachbereich Physik, Universität Kaiserslautern, Germany, November 29, 1999; Institut für Festkörperphysik, Darmstadt Technische Universität, Darmstadt, Germany, January 28, 2000.
18. "Linear and nonlinear spin waves," Seminar: Graduate Colloquium, Fachbereich Physik, Universität Kaiserslautern, Germany, January 14, 2000; Group seminar, Fachbereich Physik, Universität Osnabrück, Germany, February 18, 2000.
19. "A romp through microwave damping and relaxation ," Seminar, Naval Research Laboratory, July 24, 2000.
20. "Brillouin light scattering on nonlinear spin waves and microwave magnetic envelope solitons," The XVIIth International Conference on Raman Spectroscopy (ICORS2000), Beijing, China, August 25, 2000.
21. "Microwave ferrite science and technology," Plenary Lecture, The 8th International Conference on Ferrites (ICF8), Kyoto, Japan, September 18, 2000.
22. "Microwave loss in hexagonal ferrite - resonance linewidth, effective linewidth, spin wave linewidth, and critical modes," Invited Lecture, The 8th International Conference on Ferrites (ICF8), Kyoto, Japan, September 20, 2000.
23. "Microwave magnetic envelope solitons," Photonics Center Seminar, Boston University, Boston, Massachusetts, October 13, 2000.
24. "Brillouin light scattering on magnetic excitations," National Institute of Standards and Technology, Boulder, Colorado, December 15, 2001.
25. "Microwave envelope solitons in magnetic thin films," The 8th Joint MMM-Intermag Conference, San Antonio, Texas, January 8, 2001.
26. "A tutorial on ferrite materials - spinels, garnets, sublattices, substitutions, and magnetic properties," Materials Research Society - Spring Meeting, San Francisco, California, April 17, 2001.
27. "Microwave loss in hexagonal ferrite - resonance linewidth, effective linewidth, spin wave linewidth, and critical modes," Workshop on Ferrite Devices and Materials for Millimeter Wave Applications, IEEE International Microwave Symposium 2001, Phoenix, Arizona, May 20, 2001.

LIST OF PARTICIPATING PERSONNEL

Personnel supported and degrees granted during the current grant period are indicated below:

High school summer apprenticeships: 5
(REAP - Research Engineering Apprenticeship Program, managed by the Academy of Applied Science and funded by the ARO)

Corey Fucetola, Poudre High School (now at MIT)
Genady Gurov, Poudre High School (now at Colorado State University)
Casey Lindberg, Poudre High School (now at University of Michigan)
Kyle Thayer, Poudre High School (high school senior)
Sean Zhang, Poudre High School (high school senior)
Tim McCoy, Poudre High School (high school senior)

Undergraduate work study students: 3

Mathiew Bigelow (now at University of Rochester)
Timothy Bigelow
Michael Varney (now at University of Colorado)

Undergraduate degrees: 3

Apprentice students (Germany) 2

Reinhold Staudinger (Regensburg Technical Hochschule)
Stephan Kestl (Regensburg Technical Hochschule)

Graduate students: 5

Mark Scott (Ph.D. Candidate, degree expected May 2002)
Richard Cox (Ph.D. Candidate, degree expected May 2002)
Alexey Nazarov (Ph.D. Candidate, degree expected May 2002)
Byron Faber (M. S. degree, presently at Techtronics)
Sangita Kalarickal (Graduate student)
Anthony Gorges (Graduate student)

Master of Science degrees: 5
Ph.D. degrees granted: 0
Ph.D. degrees pending: 3

Postdoctoral fellows: 8

Dr. Hua Xia
(presently at Mechanical Technology, Inc., Albany, NY)

Dr. Hong-Yan Zhang
(presently in the Department of Chemistry, CSU)

Dr. Valeri Synogach
(presently at IBM Almaden Research Center, San Jose, CA)

Dr. Christoph Mathieu
(presently at Seagate, Inc., Rochester, MN)

Dr. Michael Wittenauer
(presently at Wittenauer Research, Fort Collins, CO)

Dr. Anuj Srivastava
(presently at Renaissance Electronics, Inc., Harvard, MA)

Dr. Pieder Beeli
(presently at University of Houston, TX)

Dr. David Menard
(presently at Seagate, Inc., Rochester, MN)

Visiting scientists: 8

Dr. Pavel Kabos
(presently at NIST, Boulder, CO)

Professor Yuri Fetisov
(presently at MIREA, Moscow, Russia)

Professor Boris Kalinikos
(presently at St. Petersburg Electrotechnical University, St. Petersburg, Russia)

Dr. Nikolai Kovshikov
(presently at St. Petersburg Electrotechnical University, St. Petersburg, Russia)

Dr. Pavel Kolodin
(presently at Channel Microwave Corporation, Camarillo, CA)

Dr. Alex Kindyak
(presently at Minsk Institute of Radio Materials, Minsk, Belarus)

Dr. Mirek Marysko
(presently at the Czech Academy of Sciences, Prague, Czech Republic)

Dr. Vladimir Kambersky
(presently at the Czech Academy of Sciences, Prague, Czech Republic)